MAN-MADE NOISE POWER MEASUREMENTS AT VHF AND UHF FREQUENCIES

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Man-made noise generated by automotive ignition, power distribution and transmission, industrial equipment, consumer products, and lighting systems degrades the performance of radio systems. Man-made noise models, derived from measurements made in the 1970s, may be inaccurate due to changes in these technologies. For example, recent man-made noise measurements performed by ITS in the 136 to 138 MHz meteorological satellite band indicated that man-made noise power in residential areas is lower than predictions by these models. However, these same measurements indicated that man-made noise in business areas has not changed. UHF man-made noise has not been comprehensively measured and modeled. This report describes UHF man-made noise measurements conducted in the Denver, CO metropolitan area in 1999. Measurement data is analyzed and results are compared to other measurements and models. These results showed that 402.5 MHz UHF noise levels in business areas were high enough to adversely affect communication system performance some of the time.

Key words: radio channel, man-made noise, impulsive noise, non-Gaussian noise, simulation of communication systems, noise measurement, noise modeling

1. INTRODUCTION

Man-made noise power was measured comprehensively 25-35 years ago [1]. These measurements, conducted from 0.25 to 250 MHz, were used to develop the CCIR [2] and current ITU-R [3] man-made noise model commonly used in radio link design to this day. Since that time no comprehensive man-made noise power measurements have been made, in spite of the fact that technological changes may have made this model inaccurate. In 1996 the Institute for Telecommunication Sciences (ITS) conducted man-made noise power measurements at 137 MHz for the National Oceanic and Atmospheric Administration (NOAA) [4] which had been tasked with converting space-to-earth VHF analog-modulated radio links to digital modulation. The measurements showed that VHF man-made noise power has decreased in residential areas and has remained constant in business and rural areas.

Predicting whether UHF frequencies would follow the same trend as VHF frequencies is difficult. For example, noise due to automotive ignition systems may have also decreased in UHF frequencies as it did at VHF frequencies; however, modern electronic devices such as personal computers and pulse-width modulated motor drives may have increased noise. All these factors point to the need for a comprehensive man-made noise measurement and analysis campaign.

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As a beginning, ITS has performed a limited set of noise power measurements at VHF and UHF frequencies in business and residential settings at 137.5 MHz, 402.5 MHz, and 761.0 MHz. These measurements were collected between April and August of the year 1999 in the Denver, CO metropolitan area. Instantaneous and long term noise power statistics were included in the measurement data analysis.

1.1. Background and Terminology

1.1.1 Noise Voltage Representations

A noise voltage is a random function of time whose behavior can only be described statistically. The time-varying noise voltage, *v(t)*, is represented as a *passband* signal centered about a carrier frequency, f_c,

$$v(t) = Re\left\{\hat{v}(t)e^{j2\pi f_c t}\right\}, \tag{1.1}$$

where $Re\{\}$ denotes the real part and $\hat{v}$(t) is the noise voltage *complex baseband* signal centered about 0 Hz that can be represented in Cartesian or polar form as follows:

$$\hat{v}(t) = x(t) + j\,y(t) = \sqrt{x(t)^2 + y(t)^2}\; e^{j \arctan\left(\frac{y(t)}{x(t)}\right)}, \tag{1.2}$$

where *x(t)* and *y(t)* are the baseband signal real and imaginary components, respectively. Both *v(t)* and $\hat{v}$(t) are random processes defined by one or more random variables. For example, if *v(t)* is *white Gaussian noise,* the real and imaginary components are independent and identically distributed zero-mean Gaussian random variables whose *power spectral density* (PSD) is flat. The corresponding amplitude is *Rayleigh distributed* while the phase is *uniformly distributed*.

1.1.2 Instantaneous Noise Power

We define the *instantaneous noise power* as

$$w = |\hat{v}(t)|^2 = x(t)^2 + y(t)^2. \tag{1.3}$$

In this report the instantaneous noise power is normalized by the average noise power due to black body radiation and thermal noise that is present in all radio systems. This average noise power is kT_0b where $k = 1.38\text{x}10^{-23}$ W/Hz/K is Boltzman's constant, T_0 = 288K is the absolute temperature, and *b* is the receiver *noise equivalent bandwidth*.

1.1.3 Statistics of Instantaneous Noise Power

The *cumulative distribution function (CDF)* of instantaneous noise power describes the probability that the noise power will not exceed a value

$$P(W_{RV} \le w) = \int_0^w p(x)dx \ , \tag{1.4}$$

where W_{RV} is the noise power random variable, w is the noise power independent variable, and $p(w)$ is the *probability density function (PDF)* of the noise power random variable. Radio engineers are concerned with the probability that the noise power will exceed a value. This probability is expressed as

$$A(w) = P(W_{RV} > w) = \int_w^\infty p(x)dx \tag{1.5}$$

and is customarily referred to as the *amplitude probability distribution* function (APD).

For white Gaussian noise, the amplitude PDF, expressed in w, is

$$p(w) = \frac{1}{w_0} e^{-\frac{w}{w_0}} \ , \tag{1.6}$$

where w_0 is $F_x^2 + F_y^2$ which is equivalent to the average power of w. The amplitude CDF, expressed in w, is

$$P(W_{RV} \le w) = 1 - e^{-\frac{w}{w_0}} \ , \tag{1.7}$$

and the APD, expressed in w, is

$$A(w) = P(W_{RV} > w) = e^{-\frac{w}{w_0}} \ . \tag{1.8}$$

Receiver performance can be predicted from the APD [5,6]. The APD, in turn, is dependent on the bandwidth of the measurement, bandwidth of the noise, and time intervals between noise pulses. The APD of zero-mean, white Gaussian noise is completely described by its mean power; therefore the performance of a receiver in white noise can be predicted from mean noise power alone.

In this report APD's are plotted on a *Rayleigh probability graph* whose axes represent the amplitude in dB above kT_0b and the percent-of-time the amplitude is exceeded. On a Rayleigh probability graph, noise with a Rayleigh amplitude distribution forms a straight line with slope -1/2 . Impulsive noise is represented by amplitudes that exceed this line at low probabilities. Continuous wave interference is represented by an approximately straight line with a slope that approaches zero as the signal-to-noise ratio increases.

Mean, median, and peak statistical functions are commonly used to characterize noise power. The mean power statistic is described in the next section. Median is the power which is exceeded 50% of the time and peak is somewhat arbitrarily defined to be the power that is exceeded 0.01% of the time. For white Gaussian noise with Rayleigh distributed amplitudes, the mean lies on the 37.0 percentile and the median and peak are 1.6 dB below and 9.6 dB above this mean value, respectively.

1.1.4 Average Noise Power

Zero-mean Gaussian noise is completely described by its variance, which is equivalent to the average noise power. The average noise power does not completely describe non-Gaussian noise but is vitally important. The *average noise power* is defined as

$$w_0 = E\{w\} \tag{1.9}$$

where $E\{\}$ denotes the expected value of its argument. The *average noise power* relative to kT_0b is called the *noise factor* and is given by

$$f = \frac{w_0}{kT_0b}\ , \tag{1.10}$$

and the *noise figure* in dB is

$$F = 10\log_{10} f. \tag{1.11}$$

Noise sources are often specified in terms of temperature, t. Temperature in K and noise factor is related by

$$f = \frac{t}{290K}. \tag{1.12}$$

1.1.5 Antenna Average Noise Power

The noise collected by the antenna originates, presumably, from widely scattered directions at or near the horizon and is therefore altered by the receiving station antenna directional gain. If *S(2,N)* is the power density coming from elevation *2* and azimuth *N*; and *g(2,N)* is the antenna directional gain relative to isotropic, the total noise power received by an antenna is

$$w_a = \frac{\lambda^2}{4\pi} \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} S(\theta,\phi)\, g(\theta,\phi) \cos(\theta)\, d\theta\, d\phi \tag{1.13}$$

where 8 is the wavelength. The corresponding antenna noise factor is

$$f_a = \frac{E\{w_a\}}{kT_0 b} \ . \tag{1.14}$$

A noise power measurement system consists of an antenna, antenna matching circuit, transmission line, and receiver. If the antenna matching circuit and transmission line are assumed to be lossless and operating at a temperature T_0, the measured noise factor is related to the antenna noise factor and receiver noise factor by

$$f_a = f - f_r + 1 \tag{1.15}$$

where f is the measured noise factor and f_r is the receiver noise factor.

1.1.6 Noise Power Statistics

Man-made noise power statistics are non-stationary in that they have been found to vary over time and location. The statistical behavior of noise power can be shown by plotting the distribution on a *normal probability graph* where random variables that are Gaussian distributed form a straight line with a slope equal to its standard deviation and a median equal to its mean. The normal probability graph can be used to display *within-the-hour*, *hour-to-hour*, and *location-to-location* noise power statistics.

1.2 Predicted Noise Power

Noise power present for 50% of the time and 50% of the locations is predicted as a function of frequency by

$$F_{am} = c - d\log_{10} f \tag{1.16}$$

where *c* and *d* are constants and *f* is frequency in MHz. F_{am} is derived from an ensemble of f_a defined in Equation 1.15. Below 200 MHz, the longstanding ITU-R model provides values of 76.8, 72.5, and 67.2 dB for *c* for business, residential, and rural environments and 27.7 dB/MHz for *d*. Above 200 MHz, Hagn [7] provides values of 49.2, 45.2, and 39.3 dB for *c* for business, residential, and rural environments and 15.8 dB/MHz for *d*. These values were based on the extrapolation of a number of lower UHF frequency spot measurements reported in the literature. Lauber [8] analyzed man-made noise power measurements obtained in 5 business, 10 residential and 2 rural environments at 600, 700, 800, and 900 MHz with a 100 kHz bandwidth. These measurements agreed well with Hagn's predictions.

Natural noise is produced by extraterrestrial and atmosphere sources. The total power is dependent upon the directionality of the source and receiving antenna. The omnidirectional antenna used in these measurements effectively attenuates the noise power of directional sources.

The sun, galactic center, cosmos, and atmospheric water vapor all have insignificant noise powers when measured with an omnidirectional antenna. Galactic noise may not be insignificant. Figure 1 summarizes noise power trends over a wide frequency range. Table 1 provides an estimate of natural and man-made noise power at the measurement frequencies.

Table 1. Natural and Man-made F_{am} (dB above kT_0b) at Measurement Frequencies

Environment/type	Frequency (MHz)		
	137.5	402.5	761.0
Business	17.6	8.1	3.7
Residential	13.2	4.1	-0.3
Rural	8.0	-1.9	-6.3
Galactic	2.8	-7.9	-14.3

For comparison, values of previous ITS measurements at 137.5 MHz are 18.0, 6.0, and 6.3 dB for business, residential, and rural environments. These measurements showed that recent business and rural noise powers are similar to older measurements but residential man-made noise may have decreased. Measurements and analysis for this report will attempt to estimate corresponding values for business and residential man-made noise power at 402.5 and 761.0 MHz.

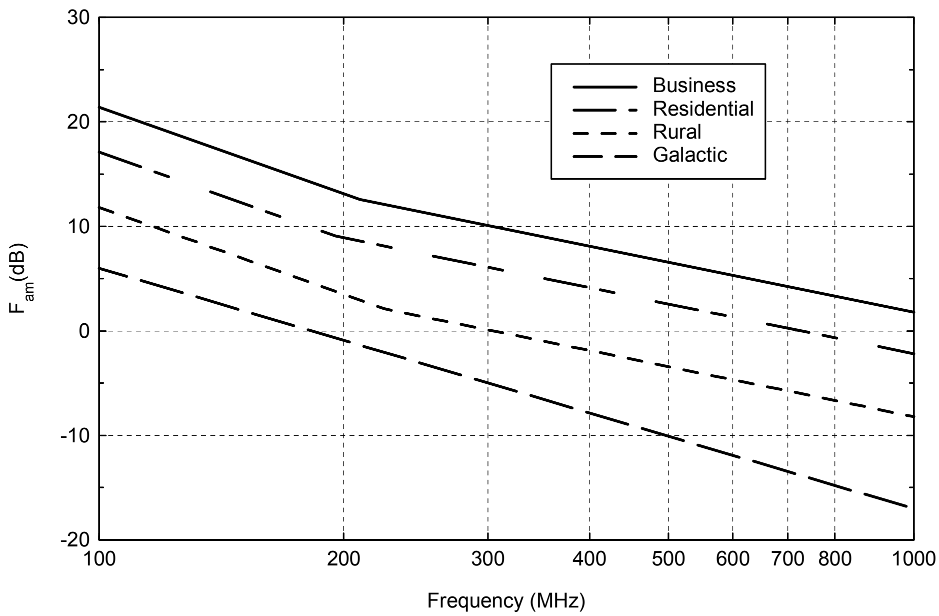

Figure 1. Natural and man-made antenna noise figures.

2. MEASUREMENTS

2.1 Frequencies

Three frequencies, 137.5 MHz, 402.5 MHz, and 761.0 MHz, were measured. The 137.5 MHz frequency is a VHF meteorological satellite space-to-earth allocation. This is the same frequency measured in the NOAA work described earlier. The 402.5 MHz frequency is in the UHF meteorological aids band extending from 400 to 406 MHz. No intentional signals at this frequency were detected at any of the measurement locations. The 761.0 MHz frequency is the center of a 6 MHz UHF television broadcast band channel. No television signals were found in this television channel or in adjacent television channels during the measurements.

2.2 Measurement Sites and Duration

Measurements were conducted in the Denver metropolitan area between April and August of the year 1999. They were acquired continuously over time periods lasting several days. This is a prudent approach for initial measurements since it allows trends in noise power statistics to be correlated with cultural patterns such as working hours and weekdays.

Two residential and two business locations in two cities were chosen to assure spatial independence. The first residential measurement was performed at a residence in Lakewood, CO approximately 10 miles west of downtown Denver, CO. The second residential measurement was performed at a residence in Boulder, CO approximately 3 miles south of downtown Boulder, CO. The business measurements were performed in downtown Boulder, CO and downtown Denver, CO.

2.3 Equipment

Man-made noise power measurements were acquired with the system depicted in Figures 2 and 3. The equipment specifications are detailed in the Appendix. The quarter-wave monopole antenna was mounted on a ground plane to assure an omnidirectional pattern whose gain is maximum at or near the horizon. The signal captured by the antenna was preselection-filtered to attenuate out-of-band power and preamplified to increase system sensitivity. The spectrum analyzer, tuned to the measurement frequency, down-converted the signal to the final intermediate-frequency where it was resolution bandwidth-filtered and log amplified. Noise power samples were obtained by digitizing the output of the envelope detector.

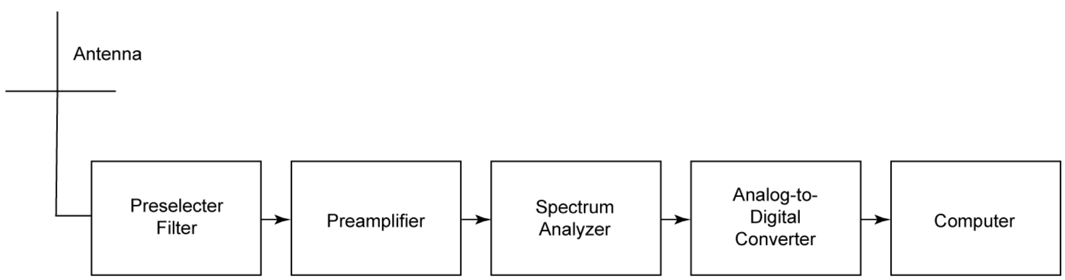

Figure 2. Block diagram of noise measurement system.

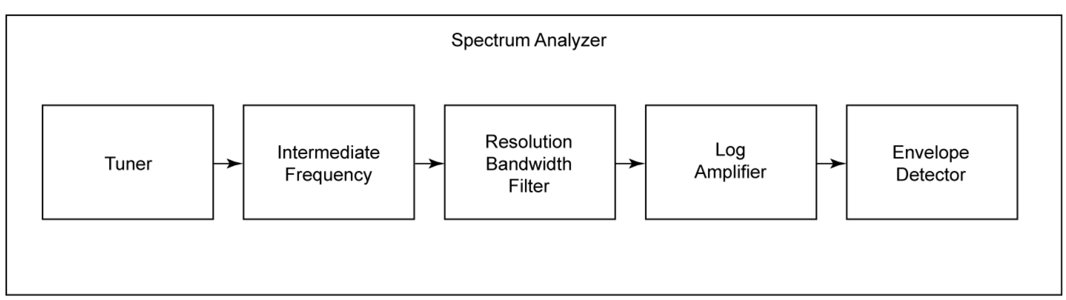

Figure 3. Block diagram of spectrum analyzer shown in Figure 2.

The resolution bandwidth filter was Gaussian shaped and had a 3-dB bandwidth of 30 kHz and a corresponding noise equivalent bandwidth of 36 kHz. The thermal noise floor, kT_0b, was approximately -128 dBm and the 1-dB compression point at the preselection filter input was approximately -55 dBm.

The slope of the log amplifier calibration curve in units of dB/volt was constant from -100 to -10 dBm spectrum analyzer input power. These input powers correspond to 0.1 to 1.0 volt direct current at the output of the log amplifier. Gain from the preselection-filter input to the spectrum analyzer input was adjusted so that noise below kT_0b was measurable and the 1-dB compression point was never exceeded. A gain of 44 dB provided a dynamic range extending from -144 dBm to -54 dBm. This range corresponds to 16 dB below kT_0b to 74 dB above kT_0b.

For business measurements the spectrum analyzer, preamplifier, and preselection filter were installed in a van. The antenna was attached to a rectangular 1.5 m by 3.0 m (5 ft by 10 ft) ground plane welded to the van roof. In this configuration the cable from the preamplifier output to the spectrum analyzer input was 3 m (10 ft) long. For residential measurements the spectrum analyzer was sheltered by a garage while the preselection filter and preamplifier were housed outside in a waterproof container. The antenna was attached to a 1.2-m (4-ft) diameter, circular ground plane. In this configuration the cable from the preamplifier output to the spectrum analyzer input was 7.6 m (25 ft) long.

Gain was accurately measured by applying a strong sinusoidal signal to the preselection-filter input and then to the spectrum analyzer input. System noise was measured by replacing the antenna with a 50-ohm load. A system noise APD is shown in Figure 4. The straight APD demonstrates that the system noise is Gaussian. System noise statistics for all other frequencies and configurations also were Gaussian distributed. Corresponding measured noise figures are reported in the following table.

Table 2. System Noise Figures (dB above kT_0b)

Configuration	Frequency (MHz)		
	137.5	402.5	761.0
Business	1.8	0.8	3.2
Residential	1.8	1.9	2.9

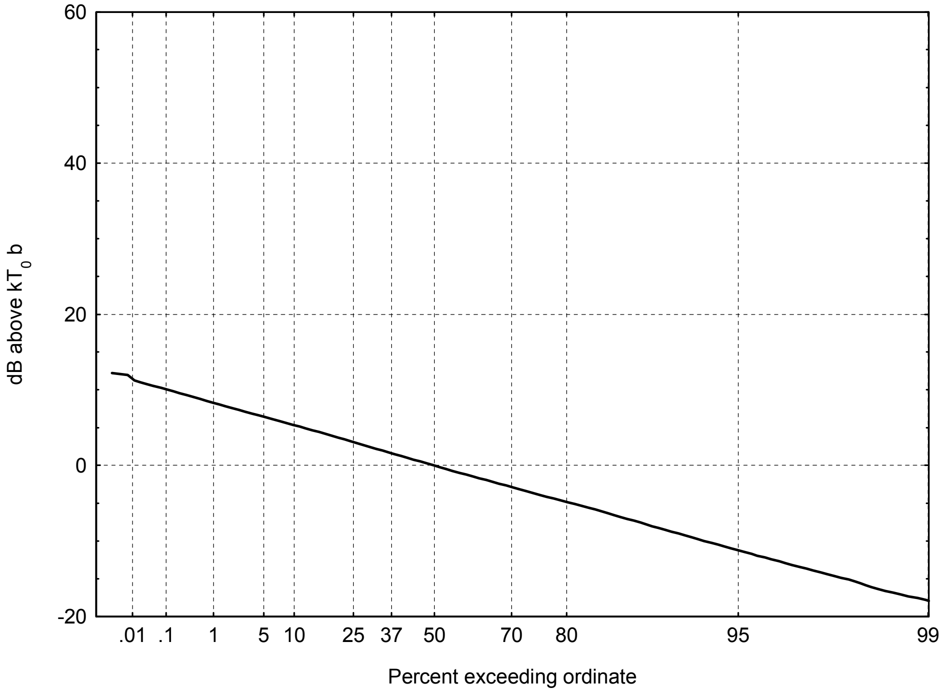

Figure 4. APD of system noise power at 137.5 MHz with residential equipment configuration. Gain and noise figure are 44.7 dB and 1.8 dB respectively.

2.4 Data Acquisition

The voltage at the output of the log amplifier was digitized with a 12-bit analog-to-digital converter (ADC). The ADC amplified the log amplifier output voltage by a factor of ten and then sampled it. The samples were converted to dBm and the gain in dB from the preselector input to the spectrum analyzer input was subtracted.

The basic noise power measurement contains 60,000 samples acquired at a rate of 1,000 samples/sec in 1-second bursts. The entire 60,000 samples were acquired in less than 3 minutes. The measurement system was not moved during this time and the noise statistics were assumed to be stationary over this time interval. Statistics of the samples were archived in a measurement histogram. The histogram bins range from -154 to -54 dBm, or 26 dB below kT_0b to 74 dB above kT_0b in 0.1-dB steps.